

Beyond Higgs

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Abstract

I discuss the Standard Model of Elementary Particle Physics and potential for discoveries of the physics responsible for electroweak symmetry breaking. I review the ideas leading to development of the Brout-Englert-Higgs mechanism that now forms the basis for the conventional Standard Model. I discuss various issues that challenge application of the Standard Model to the known physics of elementary particles. I examine alternatives to the Standard Model that address these issues and may lead to new discoveries at the LHC that go Beyond Higgs.

Introduction

The Standard Model of Elementary Particle Physics provides a remarkably accurate description of our knowledge of the basic constituents of matter and the dynamical forces that form our natural world. In 2008 we enter a new era of exploration of the TeV energy scale which will certainly bring new insights to the physics of the Standard Model and what may lie beyond.

This year the Standard Model celebrates its fortieth anniversary. In 1967 Stephen Weinberg {1} and Abdus Salam {2} independently constructed models for a unified description of the weak and electromagnetic interactions based on a dynamical theory of gauge bosons whose currents incorporated the $SU(2) \times U(1)$ gauge symmetries proposed by Sheldon Glashow {3} in 1960. The novel feature of this new theory was the incorporation a mechanism for dynamically breaking the local gauge symmetries that generated masses for the weak vector bosons consistent with the observed short-range nature of the weak forces. This mechanism had been discovered in 1964 by Peter Higgs {4} and by Robert Brout and Francois Englert {5} in their explorations of dynamical symmetry breaking and local gauge symmetries.

The Glashow, Weinberg and Salam model, as proposed in the 1967 paper of Weinberg, concerned only the weak and electromagnetic interactions of electrons and neutrinos. The theory consisted of nonabelian $SU(2) \times U(1)$ gauge bosons coupled to the electrons and neutrinos in chiral representations of the $SU(2) \times U(1)$ symmetries, the left-handed electron and its neutrino forming an $SU(2)$ doublet and the right-handed electron being a singlet. The Higgs-Brout-Englert mechanism was incorporated through the introduction a doublet of scalar bosons with a potential that favored a vacuum state with dynamical symmetry breaking. An additional Yukawa interaction was introduced to couple the chiral components of the electron to the scalar field.

In the vacuum state with dynamical symmetry breaking, the scalar field obtains a vacuum expectation value which breaks the $SU(2) \times U(1)$ symmetry down to the $U(1)$ symmetry of

electromagnetism. Using the freedom of gauge invariance, Weinberg analyzed the spectrum of physical states at tree level. In the broken symmetry vacuum, the charged vector bosons and one linear combination of the neutral vector bosons become massive with masses proportional to the vacuum expectation of the scalar field. The remaining neutral vector boson is the massless photon. With these identifications, we can determine the weak scale and weak mixing angle of the Standard Model. The electron also becomes massive through its Yukawa couplings to the scalar field. This theory is remarkably simple with only a few parameters as dictated by the $SU(2) \times U(1)$ gauge invariance of the model. The gauge interactions are described solely by the two gauge coupling constants, and the dynamical symmetry breaking requires the specification of the two parameters of the scalar potential, the scalar bare mass term and the scalar self-interaction strength.

Weinberg further speculated that the model should be renormalizable, at least in the symmetric phase. However, it was not clear at that time what role the dynamical symmetry breaking would play in the application of any program of renormalization. While we now consider the Glashow-Weinberg-Salam model as the crucial breakthrough that forms the foundation of the Standard Model, the papers had little immediate impact on the broader physics community. Indeed, it took the persistence of Martinus “Tini” Veltman and the genius of Gérard ‘t Hooft {6} to ultimately establish the renormalization of gauge field theories with dynamical symmetry breaking. Their work firmly established a new class of renormalizable field theories. The Standard Model now becomes calculable and gauge field theories are the new focus of elementary particle physics.

The Standard Model has evolved considerably from its initial incarnation as a theory of leptons. The strong interactions of hadrons have been incorporated as an $SU(3)$ gauge theory of dynamical quarks and gluons. New quarks and leptons have been discovered that include three generations of quarks and leptons whose weak interactions follow exactly the pattern established by the $SU(2) \times U(1)$ theory of Glashow, Weinberg and Salam. In this lecture we will focus on the ideas rather than the detailed analysis of particular models of elementary particle physics. In Section 1, I give a brief review of the Standard Model. In Section 2, I will discuss the origins and implications of the Higgs-Brout-Englert mechanism. In Section 3, I review some of the outstanding issues associated with our present understanding of the physics of the Standard Model. In the remaining sections, I go “Beyond Higgs” to discuss alternatives to the Standard Model which can address some of the issues of Section 3 and provide a framework for discovering the “unexpected” at the LHC and beyond.

1. The Standard Model of Elementary Particle Physics.

As mentioned in the introduction, the Standard Model has evolved considerably from the theory proposed in 1967 in “A Model of Leptons”. The $SU(2) \times U(1)$ gauge theory has been expanded to the larger symmetry $SU(3)_{\text{color}} \times [SU(2) \times U(1)]_{\text{ew}}$ reflecting the inclusion of the strong color dynamics of the constituents of hadrons. The electron and its neutrino have been replaced with three generations of chiral quarks and leptons with each generation consisting of left-handed doublets and right-handed singlets following the pattern of the original model. The mechanism of dynamical symmetry breaking is identical to the original model with one doublet of scalar mesons, the Higgs. In the minimal Standard Model the masses and weak mixing of the quarks

and leptons are require the inclusion of a large number of Yukawa couplings that determine the flavor structure of the theory.

The present Standard model is defined by a large number of fundamental parameters. There are four parameters related to the gauge boson dynamics, the three gauge coupling constants and an additional parameter, the theta angle, corresponding to the possible addition of a CP-violating topological term to the action of the color gauge fields. We can associate two parameters with the Higgs potential, the bare mass term and the scalar self-interaction, and possibly a third term associated with the vacuum energy density. The remaining parameters are associated with the Yukawa couplings for the three generations of quarks and leptons. In the most general form these interactions require three complex 3×3 matrices with a total of 54 fundamental parameters describing the Yukawa coupling constants. Only 13 of these parameters are observable due to freedom to redefine the quark and lepton fields which correspond to the six quark masses, the three lepton masses and the four parameters of the CKM matrix used to describe the mixing of the charged weak currents. Hence, the minimal Standard Model involves a total 63 fundamental parameters, with only 19 parameters having physical significance, 20 if you include the vacuum energy density. Some of the beauty and simplicity of the original formulation of the theory is certainly lost by the large number of fundamental parameters associated with the Yukawa couplings leading one to question whether these interactions are, indeed, fundamental. It is interesting to remark that the minimal Standard Model has only one parameter with the dimensions of mass, the bare mass of the Higgs doublet, which determines the weak scale at tree level.

The recent observations of neutrino oscillations only make the situation more complex as new interactions are required to describe neutrinos masses and mixing. Neutrino oscillations imply that the neutrinos must have masses and much is now known about the structure of the neutrino mixing. However, we have little direct knowledge of the mechanisms involved. A simple generalization of the minimal Standard Model would imitate the quarks by introducing three right-handed neutrinos with small Yukawa couplings that generate masses and mixings analogous to the CKM structure for quarks. This introduces 18 additional Yukawa couplings parameters of which seven are physical corresponding to three neutrino masses and four parameters associated with the weak mixing. In this formulation, lepton number would remain conserved and there would be no neutrinoless beta decay.

An alternative to the above scenario is to assume that the right-handed neutrinos have large Majorana masses that are not constrained by the electroweak gauge symmetries. At low energy the effects of these heavy neutrinos decouple leaving an effective dimension 5 operators involving two Higgs fields coupled to two left-handed neutrino fields. After dynamical symmetry breaking, these interactions generate neutrino masses and mixings. The general coupling matrix has 12 effective coupling parameters with dimensions of $1/\text{mass}$, corresponding to nine physical parameters. The observed suppression of the neutrino masses may then reflect the large mass scale of the right-handed neutrinos and neutrino physics may give us a window to view dynamics far beyond the electroweak scale.

The Standard Model has been remarkably successful in describing the physics of elementary particles. The first real confirmation of the structure of the Standard Model came with the

discovery of weak neutral currents that established the $SU(2) \times U(1)$ gauge structure. The direct observation of the charged W -bosons and the neutral Z -boson and the precision measurements of their masses and cross-sections provide stringent tests of the Standard Model. The discovery new quarks and leptons provide a more fundamental understanding of the rich mixing structure observed in rare processes including the strong suppression of flavor-changing neutral currents. The precision measurements of electroweak physics from a wide variety of experiments including results from LEP, the Tevatron and the B-factories have allowed for precise measurement of the parameters of the Standard Model and precision tests of its structure, see Figure 1. Precision measurements of CKM physics have confirmed weak mixing predicted by the quark structure of the Standard Model, see Figure 2.

The discovery of the top quark with a mass of order the electroweak scale has special significance related to its large Yukawa coupling and its contributions to the dynamics of the Standard Model beyond tree level, see Figure 3. Finally, the discovery and precision measurements of neutrino oscillations require an extension of the minimal Standard Model and may provide a window to physics much above the electroweak scale.

The Standard Model also predicts the existence of a new scalar particle, the Higgs boson, but makes no direct prediction of its mass. However, precision electroweak measurements are sensitive to the parameters that determine the Higgs boson mass through radiative corrections to the Standard Model. Constraints on the Higgs boson mass are shown in Figure 4.

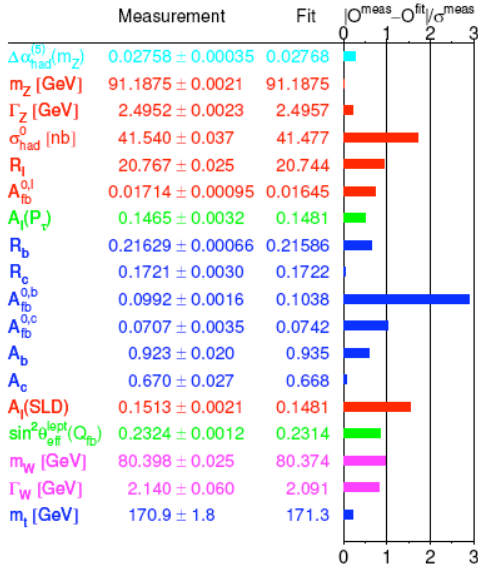


Figure 1. Pulls. (LEPEWWG'07)

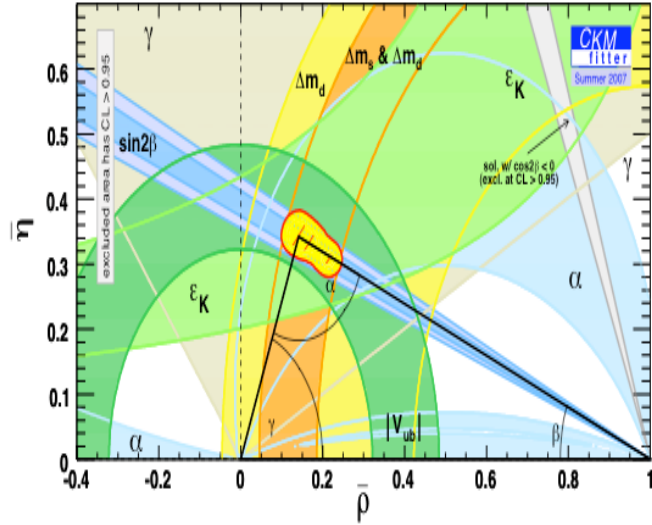


Figure 2. CKM Fits. (CKM Fitter'07)

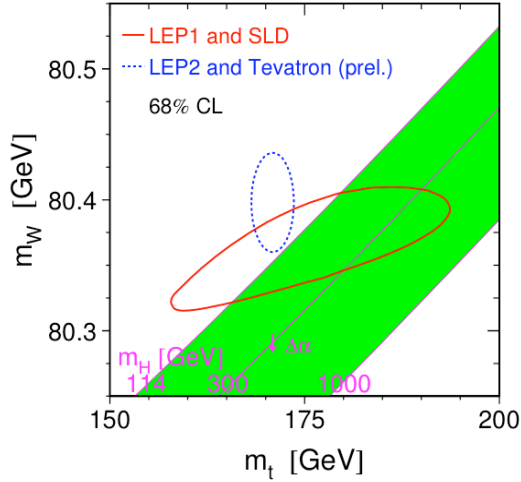


Figure 3. Precision constraints.
(LEPEWWG'07)

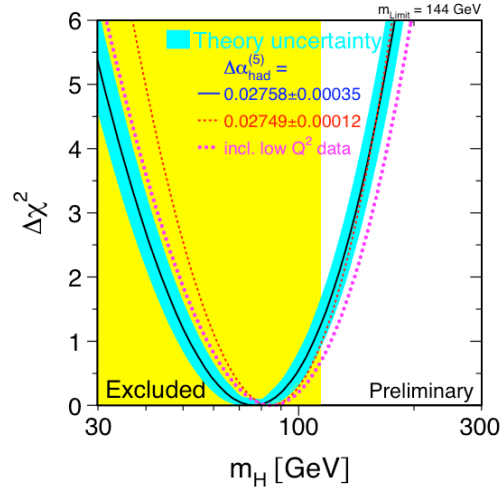


Figure 4. Higgs boson mass.
(LEPEWWG'07)

2. Origins of the Higgs Mechanism.

The Standard Model relies on the “Higgs Mechanism” to dynamically break the electroweak symmetries while preserving the underlying gauge symmetries that are essential for renormalization. In this Section I will discuss some of the ideas that led to the discovery of this mechanism in 1964. Many people played a role in developing these ideas including Higgs, Brout and Englert, Guralnik, Hagen and Kibble, Anderson, Schwinger among others.

In the late 1950's and early 1960's there were phenomenological hints to the important role that gauge field theories would play in the future of elementary particle physics. The success of quantum electrodynamics as a renormalizable quantum field theory was the prime example. The role of short-range current-current interactions became an increasing focus for dynamical description of both the weak interactions and the strong interactions of hadrons. The chiral or (V-A) structure of the Fermi theory of weak interactions became established through the observations of Robert Marshak and E.C.G. Sudarshan {7} and Richard Feynman and Murray Gell-Mann {8} which helped clarify the confusing experimental situation and led to Sheldon Glashow's work on the “partial symmetries of the weak interactions”. There were also efforts to apply Yang-Mills theory {9} to the physics of the strong interactions by Y. Fujii {10} and J.J. Sakurai {11}. Superconductivity would also be seen to play an important role in focusing attention on the role on gauge field theories and dynamical symmetry breaking.

As emphasized by Phil Anderson {12}, Yoichiro Nambu {13} and Sheldon Glashow {3}, there seemed to be a basic conflict between gauge invariance, dynamical symmetry breaking and the observed short-range nature of both the weak interactions and the strong interactions. In fact, an important success of quantum electrodynamics seemed to be the prediction of the massless photon being a direct consequence of the local gauge symmetry. Massless bosons were also expected to arise as a consequence of dynamical symmetry breaking as shown in the work of

Yoichiro Nambu {14} and Jeffrey Goldstone {15}. Hence, there seemed to be a No-Go theorem between the phenomenology suggested by both the weak and strong interactions of particle physics and the concepts of local gauge symmetry and dynamical symmetry breaking.

As mentioned above, superconductivity would play an essential role in developing the ideas that led to the discovery of the Higgs Mechanism. Superconductivity, the absence of all resistance in certain metals at low temperature, had been an outstanding problem since its discovery in 1911 by H. Kammerlingh Onnes. The fundamental breakthrough came in 1957 with the BCS theory of superconductivity developed by John Bardeen, Leon Cooper and Robert Schrieffer {16}. The BCS theory was based on the electron pairing and the formation of a new ground state with symmetries distinct from those of the normal ground state of the metal. The basic mechanisms of the BCS theory would have important analogues in elementary particle physics. These analogues include the comparisons of electron pairing with dynamical symmetry breaking, the formation of an energy gap with fermion mass generation and the Meissner effect with photon mass generation. These issues were brought into sharper focus with the development of more field theoretic formulations of the BCS theory including the work of N.N. Bogoliubov {17}, Yoichiro Nambu {18} and Phil Anderson {12}. In particular, there was considerable focus on the nature of gauge invariance and the role of dynamical symmetry breaking. However, in superconductivity, there seemed to be no evidence for the massless excitations that seemed to be inevitable from the mathematical descriptions of particle physics. Indeed, in 1963 Anderson {19} argued that the plasmon excitations in a superconductor could be identified as massive photons and that speculated on the possible implications for mass generation in Sakurai's gauge model of strong dynamics.

Despite the success of the theory of superconductivity, the puzzle of the No-Go theorem in particle physics had become more severe. In 1962, Jeffrey Goldstone, Abdus Salam and Stephen Weinberg {20} proved an important theorem concerning the Nambu-Goldstone conjecture on dynamical symmetry breaking. They showed that any theory with dynamical symmetry breaking and explicit relativistic covariance would necessarily have a massless boson in its spectrum of excitations. This seemed to close the door on the physical applications of dynamical symmetry breaking in particle physics.

In 1964 Peter Higgs {4} found an exception to the assumptions used in the proof of the No-Go theorem. He argued that theories with massless gauge bosons were not relativistically covariant as the gauge field quantization depended on an additional reference four-vector. Of course, physical quantities would not depend on this reference vector, but the essential exception had been found to the conditions of the theorem. Higgs further gave an explicit example where the massive vector boson arose as an excitation of a gauge invariant combination of the Nambu-Goldstone field and the gauge field. Robert Brout and Francois Englert {5} independently arrived at similar conclusions by computed the self-energy of Yang-Mills gauge bosons in the presence of matter with dynamical symmetry breaking. They showed that the gauge bosons will become massive while preserving gauge invariance if there is dynamical symmetry breaking, or to quote from their paper “vector bosons which are coupled to currents that ‘rotate’ the original vacuum are the ones that acquire mass”. The two essential elements of the No-Go theorems have conspired together to avoid the theorems completely. Gauge bosons can acquire mass in the presence of dynamical symmetry breaking. It is curious that this important breakthrough did

not have immediate consequences. The application to the weak interactions would not occur until the work of Weinberg and Salam in 1967. The strong interactions would have to wait until the development of quantum chromodynamics in the early 1970's where the short-range nature of strong interactions would result from confinement and not dynamical symmetry breaking in the form considered by Higgs, Brout and Englert.

3. Classic Issues with the Standard Model.

While the Standard Model has been remarkably successful in its description of the natural world, many physicists do not believe it represents the ultimate fundamental theory of elementary particle physics. In this section I will discuss some of the classic issues concerning the validity of the Standard Model, particularly as we begin to probe more deeply using energy scales substantially above the electroweak scale. Most of these issues do not question the validity of the Standard Model as an effective theory but rather question whether the values of particular parameters make sense at a fundamental level.

3.1. The hierarchy problem relates to the question of what sets the scale of electroweak symmetry breaking in the presence of quantum corrections. The Higgs mass parameter is particularly sensitive to radiative corrections as individual diagrams have a quadratic sensitivity to the high energy processes appearing in the loops. At one loop, the dominant contributions come from virtual process involving the Higgs scalar, the top quark and the gauge boson as shown in Figure 5 and in Equation 1.

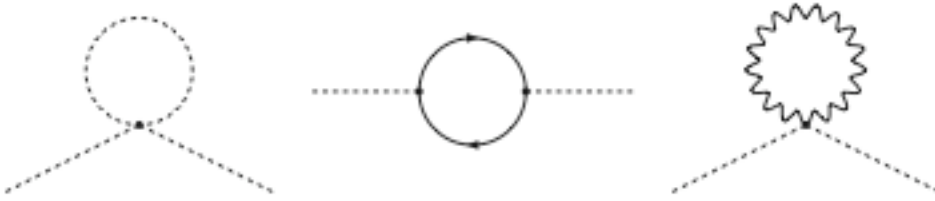


Figure 5. Radiative corrections to the Higgs mass parameter.

$$\Delta M_H^2 = \frac{3}{2} \frac{\lambda_H}{(4\pi)^2} \Lambda_{higgs}^2 - 6 \frac{y_{top}^2}{(4\pi)^2} \Lambda_{top}^2 + \frac{3}{4} \frac{3g^2 + g'^2}{(4\pi)^2} \Lambda_{gauge}^2 \quad (\text{Eq. 1})$$

In evaluating the contributions from the diagrams in Figure 5, I have used a sharp momentum cutoff for each loop with a different cutoff for each loop to emphasize that evaluating these diagrams with a given cutoff does not give a proper representation of the actual ultraviolet contributions to the Higgs mass parameter but only indicates the ultraviolet sensitivity of the individual contributions. There is no such thing as a running mass parameter in contrast to the running coupling constants that describes an effective field theory at a given energy scale. Most of the contributions to the integrals come from the neighborhood of the cutoff scale and small changes in the different cutoffs can drastically modify the various contributions to the sum. Of course, the quadratic divergences may be completely spurious if approximate scale invariance controls the short distance physics {21}.

Conventional solutions to the hierarchy problem, such as supersymmetry, use symmetries to relate the various terms contributing to the mass-shift. It is important that these symmetries control both the relationships between coupling constants and the ultraviolet contributions to the corresponding integrals.

3.2. Another classic issue with the Standard model is the strong CP problem related to the theta angle contribution to the QCD action mentioned in Section 1. This term is odd under CP transformations and can generate nonperturbative corrections to various processes including the neutron electric dipole moment. These contributions have been estimated in QCD {22} to be

$$|d_n| \sim 5 \cdot 10^{-16} \text{ ecm} \cdot \theta, \quad 0 \leq \theta \leq 2\pi. \quad (\text{Eq. 2})$$

Recent measurements of Baker et al {23} give an upper limit on the neutron electric dipole moment of $|d_n| < 2.9 \cdot 10^{-26} \text{ ecm}$, which implies $\theta < 10^{-10}$. Attempts to give a dynamical explanation of the small size of the effective theta angle go beyond the Standard Model. Most attempts require new symmetries, such as a Peccei-Quinn symmetry {24}, combined with dynamical symmetry breaking to allow the theta angle to relax to zero. The consequence is the existence of a new pseudo-Nambu-Goldstone boson, the axion {25, 26}. Electroweak scale axions were ruled out experimentally in the 1980's but viable models with invisible axions are still possible. There are many new searches {27} for axion-like particles that cover a wide range of mass and coupling strength. The axion could also be a possible component of the dark matter in the universe.

3.3. As mentioned in Section 1, the Standard Model invokes a huge array of Yukawa couplings to generate quark and lepton mass and mixing. The large mass hierarchies observed for the quarks and charged leptons imply the wide range of Yukawa couplings shown in Figure 6 with $g \sim 1$ for the top quark and $g \sim 10^{-6}$ for the electron. While these are simply fundamental coupling parameters in the Standard Model, there have been many attempts to provide a deeper explanation for the structure observed in the pattern of the Yukawa couplings. Speculations include family symmetries, composite structure, textures in grand unified theories or structure related to the geometry of extra dimensions of space-time.

If we include the recent developments in neutrino physics the issues become more complex. If neutrino masses have a CKM-like structure with three right-handed neutrinos, the hierarchy of Yukawa couplings is extended to $g \sim 10^{-13} - 10^{-11}$. In this scenario there would be no lepton number violation and no neutrinoless double beta-decay. Another alternative scenario uses only the left-handed neutrinos but adds dimension 5 operators to generate neutrino masses. In this case the small neutrino masses would reflect a new high-energy scale for the physics that generates these effective operators. Many other possibilities are possible given our present limited knowledge of neutrino masses and mixing.

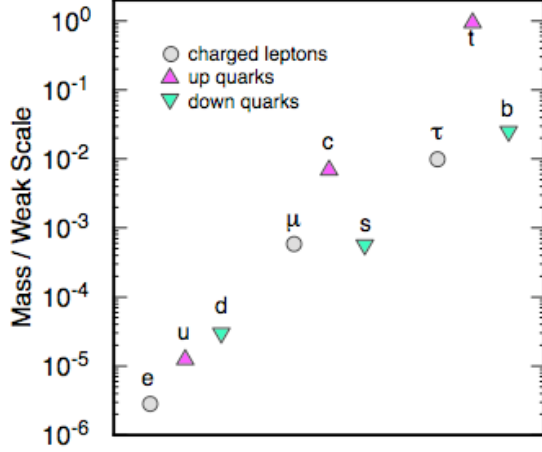


Figure 6. Yukawa coupling hierarchies.
(C. Quigg, 2007)

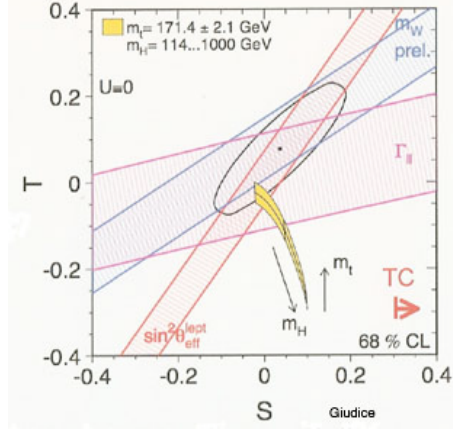


Figure 7. S,T constraints.
(G. Giudice, 2007)

3.4. Precision measurements at LEP, the Tevatron and the B-factories provide strong constraints on physics beyond the Standard Model. The clash between the sensitivity of precision electroweak data and the stabilization of the radiative corrections that determine the electroweak scale is known as the LEP Paradox or the Little Hierarchy Problem. Theories with new strong dynamics are normally expected to make additional contributions to low energy physics through higher dimension operators such as those shown in Equation 3.

$$\frac{|H^+ DH|^2}{\Lambda^2}, \frac{|D^2 H|^2}{\Lambda^2}, \frac{((H^+ \sigma^a H) W_{\mu\nu}^a B^{\mu\nu})}{\Lambda^2}, \dots \quad (\text{Eq.3})$$

These operators generate corrections to the S,T,U parameters that measure deviations to the Standard Model and are constrained by the precision measurements as shown by the fits in Figure 7 {28}. The constraints imply strong coupling scales must be large, $\Lambda \sim 5 - 10 \text{ TeV}$, while the radiative corrections to the Higgs mass parameter seem to require new physics at scales, $f \sim \Lambda/4\pi \sim 0.5 - 1 \text{ TeV}$ with appropriate symmetries that protect the stability of the electroweak scale.

3.5. Recent developments in cosmology and astrophysics can provide new constraints on the Standard Model or evidence for new physics. The observations of cosmological dark energy can be interpreted a measurement of a small vacuum energy density, $\sim (0.002 \text{ eV})^4$. Unfortunately, there is no precise prediction of the vacuum energy density in the Standard Model or in the usual formulations of supersymmetric models as there are parameters that can be arbitrarily adjusted to fit the measurements. However, as in the case of the Higgs mass parameter, the naïve estimates of the radiative corrections to the vacuum energy are huge compared to the measured values and suggest a severe fine-tuning problem and a challenge for any dynamical explanation of the discrepancy.

The fact that the observed matter in the universe is made of baryons and not antibaryons provide another issue for the Standard Model. The cosmological baryon to photon ratio is observed to be $\sim 6 \cdot 10^{-10}$. Standard model processes do generate a baryon asymmetry but are highly suppressed relative to the observations.

Astrophysical observations indicate the presence of a large dark matter component in the universe. The dark matter to baryonic matter ratio is of order $\sim 6/1$. The evidence for dark matter provides a definite signal of physics beyond the Standard Model.

Many of the issues discussed in this section concern the quest for a deeper understanding of the observed values for various parameters of the Standard Model but do not necessarily dispute the validity of its dynamics. The electroweak scale hierarchy, the value of the strong CP-violating theta angle, the Yukawa coupling hierarchies and the vacuum energy density are not predictions of the Standard Model but can be accommodated by adjusting its parameters. The neutrino masses and mixings can also be viewed as an extension of the Standard Model without modifying basic structure of the Higgs mechanism for the dynamical breaking of the electroweak symmetries. Dark matter is an exception, as it would require additional physical degrees of freedom beyond those contained in the Standard Model. Of course our understanding of the nature of the physics at the TeV scale may soon be dramatically altered as we explore the “unexpected” at the LHC and other facilities.

4. Beyond Higgs – Supersymmetry.

We now wish to explore a variety of ideas that go substantially beyond the physics of the Standard Model and directly confront many of the issues described in the previous section. Models based on supersymmetry have been extensively studied and have the potential to resolve many of the issues that challenge our understanding of the Standard Model.

Supersymmetry was initially proposed as an extension of space-time symmetries by Julius Wess and Bruno Zumino {29} in 1974 based on symmetries discovered exploring the consistency of string theories. Supersymmetry relates fermions to bosons and particles with different spins that requires a novel extension of the Poincaré symmetries of relativistic particles and can be viewed as a step into fermionic extra dimensions. Models based on supersymmetry provide the most anticipated extensions of the Standard Model and have been explored extensively both theoretically and experimentally. The search for evidence of supersymmetry will be a prime focus of initial studies at the LHC.

Supersymmetry makes some novel predictions concerning the behavior of the higher order corrections that have plagued the Standard Model. In the supersymmetric limit, nonrenormalization theorems predict the vanishing of certain radiative corrections including the analogue of the Higgs mass parameter and the vacuum energy density. Of course, we do not observe a supersymmetric world and supersymmetry must be broken at the presently accessible energy scales. However, the energy scale where supersymmetry is restored must not be too far away if supersymmetry is to resolve many of the issues discussed in Section 3. A resolution of the hierarchy problem associated with the stabilization of the electroweak scale focuses on a TeV scale for supersymmetry breaking. Many mechanisms have been proposed to provide a

dynamical understanding of origin of supersymmetry breaking along with predictions for the low energy phenomenology. Since supersymmetry is associated with the symmetries of space-time, gravity must also be modified to include supergravity or string theory.

Supersymmetric models have many attractive aspects. Like the Standard Model, most supersymmetric models are weakly coupled and perturbation theory can be used to make reliable predictions. Particle spectra and couplings are highly constrained by supersymmetry. For example, most viable supersymmetric models predict a light Higgs boson with a mass less than ~ 130 GeV. We have mentioned the role of supersymmetry in the stabilization of the electroweak scale where cancellations between fermion and boson loops eliminates the ultraviolet sensitivity of the higher order corrections to the Higgs mass parameter. Radiative corrections involving the top quark can drive the instabilities that lead to electroweak symmetry breaking. Precision measurements of the gauge coupling constants suggest the unification of gauge couplings at high energy in supersymmetric models. A number of new particles are predicted to exist near or below the TeV scale and can provide a solution to the Little Hierarchy problem. Detailed calculations in some supersymmetric models suggest a possible leptogenesis solution for cosmological baryon asymmetry {30}. In supersymmetric models, a discrete R-parity that distinguishes the Standard Model particles from their supersymmetric partners also provides candidates for the dark matter in the universe.

Is supersymmetry about to be discovered? Global fits have been used to constrain the parameters of the Standard Model as seen in Section 1. Indications from a similar global fit to a constrained version of the minimal supersymmetric standard model, CMSSM, by O. Buchmueller et al {31} suggest a physical Higgs boson with mass very close to the LEP limit and a relatively light spectrum of superparticles. Details of the analysis are presented in the lecture of Frédéric Ronga {32}. The spectrum of states is similar to the scenario of CMS Point 1 with the lightest supersymmetric states being a neutralino, a chargino and stlepons in the mass range of 110 – 200 GeV with squarks and gluinos in the range of 500-600 GeV. Figure 3 of Buchmueller {31} compares the CMSSM and Standard Model fits for a variety precision measurements with very similar results. If this is a true indication of nature then supersymmetry is, indeed, just around the corner.

5. Beyond Higgs – Large Extra Dimensions.

The Standard Model hierarchy problem is usually represented as the conflict between the electroweak scale of 100 GeV and an ultraviolet sensitivity Higgs mass parameter to very high ultraviolet scales of 10^{19} GeV corresponding to the Planck scale of gravity or a fundamental string theory. A novel solution to the hierarchy problem suggests that these high ultraviolet scales may be an illusion that appears because we live in a universe with large extra dimensions of space-time. Extra dimensions are not a new idea as Kaluza-Klein theory had been proposed in the 1920's to identify electrodynamics as a component of gravity in a five dimensional space-time. Consistency of most string theory models also require there to be ten dimensions of space-time where the six additional dimensions are presently too small to observe.

5.1. In 1998, Arkani-Hamed, Dimopoulos and Dvali {33} proposed a novel theory of large extra dimensions where gravity spreads out into the bulk of the extra dimensions while matter fields

remain localized. They observed that the Planck mass scale would be reduced by the volume of the extra dimensions and for large extra dimensions represents a possible solution to the hierarchy problem. Their theory predicts that there should be a modification of the gravitational force laws at short distances that depends on the size and number of extra dimensions. String models with electroweak scale extra dimensions had also been proposed by Lykken {34}.

These ideas have simulated many experiments to search for modifications gravity and provide explicit evidence for the existence of extra dimensions. So far, the experiments have not seen any deviations from normal gravity. The most stringent limits come from the torsion balance experiments of the Adelberger Group {35} at the University of Washington. Their 2006 exclusion limits are shown in Figure 8 and can be represented as a limit on the size of the extra dimensions. Assuming one extra dimension, the present limit gives $R_{ED} \leq 44\mu\text{m}$.

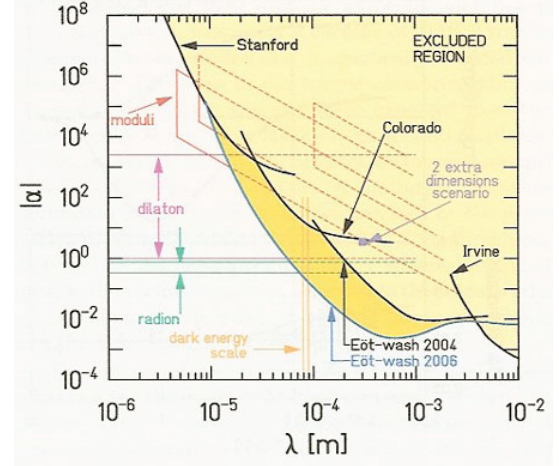


Figure 8. Modified gravity constraints.
(D.J. Kapner et al, 2006)

5.2. There are many alternative ideas concerning the role of extra dimensions and their impact on the physics of the Standard Model. In 2001, Applequist, Cheng and Dobrescu proposed a theory of Universal Extra Dimensions {36} where all Standard Model fields propagate in the extra dimensions in addition to gravity. The usual Standard Model particles are identified with the massless states, or zero modes, of the five dimensional fields. The geometry of the extra dimensions can impact the nature of the zero modes and the spectrum of excited Kaluza-Klein states. For example, in a particular UED model with two large extra dimensions, orbifold symmetries predict the chiral structure of the Standard model and global anomalies of the compactified theory require that there be $3n$ generations of quarks and leptons. Residual discrete symmetries associated with the six dimensional Lorentz symmetry suppress proton decay, and a KK-parity implies the existence of a stable dark matter candidate. Neutrinos are expected to have a Dirac structure that prohibits neutrinoless double beta decay and the model predicts a large value of the neutrino mixing angle, Θ_{13} . The presence of the extra dimensions can therefore impact the structure the effective field theory we presently observe in addition to providing new dynamics from particles propagating in the extra dimensions.

5.3. Another solution to the hierarchy problem arises for warped extra dimensions following a novel suggestion by Lisa Randall and Raman Sundrum in 1999 {37}. A large negative cosmological constant in the higher dimensional space-time will generate a curved background corresponding to an anti-deSitter (AdS) space which is described by the metric,

$$ds^2 = \exp(-kaz) \left(dx_\mu^2 \right) - a^2 dz^2. \quad (\text{Eq. 4})$$

In this picture the hierarchy problem is translated into how the various physical degrees of freedom are localized in the coordinate of the extra dimension, z .

In these models the universe can end on four dimensional surfaces, or branes, with gravity localized on the Planck brane at $z=0$ and an infrared, or IR, brane located at a position corresponding to the TeV energy scale. There exist many models with matter and gauge fields located in the bulk and/or on the branes. Boundary conditions determine how the low energy states are localized in the extra dimension coordinate, z , as well as the spectrum of low-lying Kaluza-Klein modes. A novel feature of this solution to the usual hierarchy problem is the possibility that the large spectrum of Yukawa coupling constants discussed in Section 1 could arise dynamically from wavefunction overlaps for states that are located at different positions in the extra dimension. There are rich possibilities for model building and for structure beyond the Standard Model.

The physics of AdS space may have a completely different but equivalent interpretation in terms of strongly coupled quantum field theories in four dimensions. In 1998, Juan Maldacena [38] argued that conformal gauge field theories in four dimensions should have a dual description as theory of gravity in a five dimensional AdS space, at least in certain “large N ” limits. In this case, we might be able to interpret the physics of the Randall-Sundrum scenario in equivalent terms as the dynamics of strongly coupled field theories in four dimensions. Maldacena’s conjecture has stimulated intense activity exploring all aspects of this duality and its impact on the physics of AdS space and the dynamics of strong coupling field theory.

6. Beyond Higgs – Strong Dynamics.

Strong dynamics has long provided a conceptual alternative for the mechanism of dynamical symmetry breaking and a solution to the hierarchy problem in the Standard Model. In 1979, Weinberg and Susskind observed that the mechanism for the dynamical breaking of chiral symmetries in quantum chromodynamics could be adapted to the problem of electroweak symmetry breaking. In these technicolor models, the symmetry breaking arises from techniquark condensates rather than elementary scalar bosons. Because of the difficulties associated with the strong dynamics, the analysis of these models has relied on analogies with QCD. The Maldacena duality discussed in the previous section may provide an alternative method for analyzing models based on strong dynamics.

6.1. Using the QCD analogy, technicolor gauge bosons provide the confining forces and techniquarks provide the chiral symmetries associated with the electroweak physics. A simple $SU(4)$ technicolor model with gauge coupling unification would be expected to confine techniquarks at the TeV scale and generate dynamical symmetry breaking at the electroweak scale. While this would seem to provide a natural explanation of the W and Z boson masses, it has proven more difficult to generate fermion masses and realistic dynamics. Extended technicolor models were soon proposed to provide coupling between the techniquarks and the usual quarks and leptons establish a mechanism for transmitting electroweak symmetry breaking to the fermion sector. Unfortunately, the simple models based on QCD were not successful. The wide range of quark and lepton masses, particularly the heavy top quark, is difficult to achieve while preserving a natural explanation for the suppression of flavor-changing neutral currents.

As mentioned in Section 3, precision measurements of the S,T,U parameters place severe constraints on models with strong dynamics at the TeV scale and seem to rule out models based on the dynamics analogous to QCD.

6.2. Alternatives to the extended technicolor scenarios have been considered. In walking technicolor models, the dynamics is presumed to be that of a pseudo-conformal field theory in contrast to the dynamics of QCD. Operators can have large anomalous dimensions that modify the scaling laws that determine the fermion mass spectrum and other quantities in the theory. While more realistic models can be achieved in walking technicolor models, there are still strong constraints from the precision electroweak data and detailed predictions for specific models are difficult due to the nature of strong dynamics.

6.3. The top quark Yukawa coupling constant is large, $g_{top} \sim 1$, suggesting the possibility that the top quark may play a special role in electroweak symmetry breaking and the generation of fermion masses. In top quark condensate models, the large couplings in the top quark sector reflect the composite nature of the Higgs boson field. The top quark also plays a special role in a variety of models including topcolor, topcolor-assisted-technicolor and top-seesaw models {39}. The special dynamics of the top quark and its connection to strong dynamics may reflect connections to higher dimensional structures in field theory. Methods for deconstructing higher dimensional models often give a geometrical perspective to the physics we observe in four dimensions.

7. Beyond Higgs – Little Higgs Models.

Precision electroweak data highly constrain models based on strong dynamics as higher dimension operators that could make generic contributions to electroweak physics seem to be suppressed by scales of 5-10 TeV or larger. A “little” hierarchy problem arises through the tension between fine-tuning the corrections to the Higgs mass parameter and the higher scale of new strong dynamics. While not as dramatic as the fine-tuning issues associated with the Planck scale, the little hierarchy problem has become more severe as the precision of the electroweak data has improved.

Little Higgs models are an attempt to solve this little hierarchy problem by considering the physical Higgs boson to be a composite state of the strong dynamics associated with this higher scale. This is in contrast to technicolor models which generate electroweak symmetry breaking through strong dynamics but no physical Higgs boson. To avoid fine-tuning, additional symmetries must be invoked to provide dynamical mechanisms for canceling the large radiative corrections that destabilize the electroweak scale.

7.1. As proposed by Nima Arkani-Hamed, Andrew Cohen and Howard Georgi {40} in 2001, Little Higgs models are based on an enlarged set of symmetries that are dynamically broken at the strong dynamics scale of 5-10 TeV. An enhanced set of Nambu-Goldstone bosons that includes the physical Higgs boson are generated as a result of the dynamical symmetry breaking. There is also an enhanced spectrum of gauge bosons whose interactions break the new symmetries down to those of the Standard Model. The crucial idea in Little Higgs models is the concept of collective symmetry breaking. Individual terms do not break all of the enhanced

symmetries but must act collectively. In this case, the spectrum of massless Nambu-Goldstone bosons is enhanced to include the physical Higgs boson. The enhanced symmetries protect the mass of the physical Higgs boson and it remains massless even in the presence of radiative corrections. Only when two or more terms act collectively will the physical Higgs boson become massive. In this case, the one loop radiative corrections will not generate the quadratic divergent terms that are most sensitive to the strong dynamics scale. The quadratic divergences are canceled by contributions loops involving particles of the same spin in contrast to supersymmetry. The spectrum of states is doubled from that of the minimal Standard Model with the additional states having masses of order 1 TeV. Above the 1 TeV scale, the symmetries of the Little Higgs model dictate that leading divergences cancel between loops involving Standard Model particles and their heavy partners. This cancellation stabilizes the radiative corrections without generating large corrections to the electroweak observables.

Studies of various Little Higgs models found that the enhanced symmetries did not sufficiently suppress corrections for some tree-level processes. Hsin-chia Cheng and Ian Low {41} proposed that these contributions could be suppressed with the addition of a new discrete symmetry, T-parity. Standard Model particles are T-even while the massive partners are T-odd. T-parity is similar to R-parity in supersymmetry as can be used to eliminate direct mixing between Standard Model particles and the T-odd states. As a consequence, T-odd states must be pair produced in processes involving Standard Model particles and the lightest T-odd state would be stable and a possible candidate for dark matter. This stability has recently been challenged by the work of Hill et al {42} who argue that T-odd states should decay through anomalies in a manner similar to the two photon decay of the neutral pion.

7.2. The Littlest Higgs model, proposed by Arkani-Hamed and collaborators {43}, is based on an $SU(5)$ global symmetry and has been the subject of considerable analysis. The $SU(5)$ symmetry is dynamically broken to $SO(5)$ at the strong dynamics scale of 5-10 TeV. The physics below the symmetry breaking scale is described by the dynamics of Nambu-Goldstone bosons corresponding to the coset space, $SU(5)/SO(5)$. The dynamics of the Nambu-Goldstone boson is described by a nonlinear chiral Lagrangian with a coupling related to a scale, f , with $4\pi f \sim 5 - 10$ TeV. The electroweak gauge symmetries are enhanced to $(SU(2) \times U(1))^2$ which are dynamically broken down to electromagnetism according to

$$(SU(2) \times U(1))^2 \rightarrow (SU(2) \times U(1))_{\text{ew}} \rightarrow U(1)_{\text{em}} \quad (\text{Eq. 5})$$

where the first breaking occurs at the scale $f \sim 1$ TeV while the second breaking occurs at electroweak scale, ~ 175 GeV. The top quark sector is also modified with the addition of a vectorlike top quark as in the top seesaw models. As mentioned above, the Standard Model particles, W, Z, top quark and the physical Higgs boson are all expected to have masses near the electroweak scale while their partners have masses associated with the higher scale f . Requiring T-parity requires an additional discrete symmetry of the gauge coupling constants and a further enhancement of the top quark sector.

Precision electroweak constraints imply that the scale f could be as low as 500 GeV in the models with T-parity {44}. The lightest T-odd particle is expected to be the heavy gauge boson

associated with the $U(1)$ symmetry. There is a rich collider phenomenology {45, 46} involving the search for new states and the dynamical mechanisms of the Littlest Higgs model. Andrzej Buras and collaborators {47} have also made systematic studies of rare processes including K- and B- decays. They find that enhancements of certain rare decays are possible in the Littlest Higgs model which could give large corrections to the Standard Model processes that are highly suppressed.

It is interesting that precise statements can be made about the effective dynamics of Little Higgs models despite their origin in a theory of strong dynamics. This occurs because the symmetries control the dynamics of the Nambu-Goldstone bosons at low energies which greatly restricts the number of effective parameters needed to describe physics at a certain level of precision.

Conclusions.

We have yet to fully understand the dynamical mechanisms of electroweak symmetry breaking. The Standard Model appears to work for now but its basic dynamics, the Higgs mechanism, has yet to be tested as we have not observed the physical Higgs boson or any of its couplings. The Standard Model requires many Higgs parameters mostly related to the Yukawa coupling constants that are needed to give mass to the fermions of the Standard Model. It is difficult to believe that each of these dimensionless parameters is a fundamental quantity in nature. Neutrinos, dark matter and axions may require new dynamics which could replace the Standard Model and modify our understanding of the role of the Higgs mechanism.

Many directions are being explored for new physics and a more fundamental understanding of the physics of elementary particles. Supersymmetry has a rich phenomenology of new states and dynamical mechanisms which may provide our most profound understanding of physics at the shortest distance scales. The possible existence of extra dimensions of space-time could dramatically alter our conceptual picture of the universe. There are many new scenarios including flat and warped dimensions along with branes and other phenomena that relate to the distribution of matter in the extra dimensions. Warped extra dimensions may provide a dual nonperturbative description of four dimensional gauge theories and a deeper insight to theories based on strong dynamics. The phenomenology of strong dynamics has included the possible role of a heavy top quark as well as composite models for the physical Higgs boson such as technicolor and Little Higgs models which address some of the outstanding issues of the Standard Model.

We may be on the verge of revolutionary times in elementary particle physics where the tyranny of the Standard Model may finally be overturned. Our first hints come from the Tevatron, neutrino physics, the B-factories and cosmology. As we begin to probe the physics of the TeV scale at the LHC we look forward to discovering the “unexpected” with new particles and new dynamics that will dramatically alter our view of the subnuclear world. The development of future facilities to make precision measurements and the ability to observe very rare processes may provide windows to physics even beyond the TeV scale.

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